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RADAR OBSERVATIONS OF NEAR-EARTH ASTEROIDS

Steven J. Ostro*

Radar echoes can furnish high-resolution images of near-Earth asteroids, reveal their rotation states and metal abundances, and improve the accuracy of trajectory predictions a thousandfold, a capability that is important for asteroids making very dose Earth approaches and that can dramatically reduce the cost and risk of spacecraft missions.

Much useful information about physical and dynamical properties can be obtained from radar observations of near-Earth asteroids (NEAs) that come within reach of groundbased radar telescopes[1]. Resolution of echoes in Doppler frequency and/or time delay can be used to synthesize 1-D or 2-D images that show a target's size, shape and rotation. Disc-integrated measurements also have value, because the wavelengths of NEA radar systems (3.5 or 13 cm) provide sensitivity to near-surface bulk density and structure larger than a few centimeters, and because metal, which is much more abundant in iron/stony-iron meteorites than chondrites, influences radar reflectivity dramatically y.

Since delay/Doppler measurements are orthogonal to optical, angular-position measurements and generally have much finer fractional precision, they permit significant improvement in estimates of orbits and hence in the accuracy of prediction ephemerides[2]. NEA measurements have achieved a time-delay precision of 0.125 μs (19 m) and a Doppler precision of 0.0083 Hz at 8510 MHz (O. 15 mm/see in radial velocity). Radar aperture synthesis measurements (multi-baseline interferometry) can estimate angular positions to a few hundredths of an arcsecond, further improving orbital solutions. For a newly discovered object, radar can help to ensure optical recovery during subsequent close approaches, obviating the need for optical follow-up astrometry. Even for asteroids with secure orbits, radar astrometry can significantly shrink positional error ellipsoids for decades, with direct implications for predictions of close approaches and for the navigation of spacecraft to asteroids.

Figure 1 shows a Goldstone real-time display of a Geographos delay-Doppler image. Power above half the peak value is plotted for 64 Doppler-frequency cells and 127 time-delay cells. The delay-Doppler resolution (1 μs by 2.9 Hz) corresponds to spatial resolution of 150 m x ~150 m; prior knowledge of the spin vector from optical lightcurves indicated that our view was equatorial and set the Hz-to-m conversion.

*Mailstop 300-233, Jet Propulsion Laboratory, Pasadena, California 91109-8099,

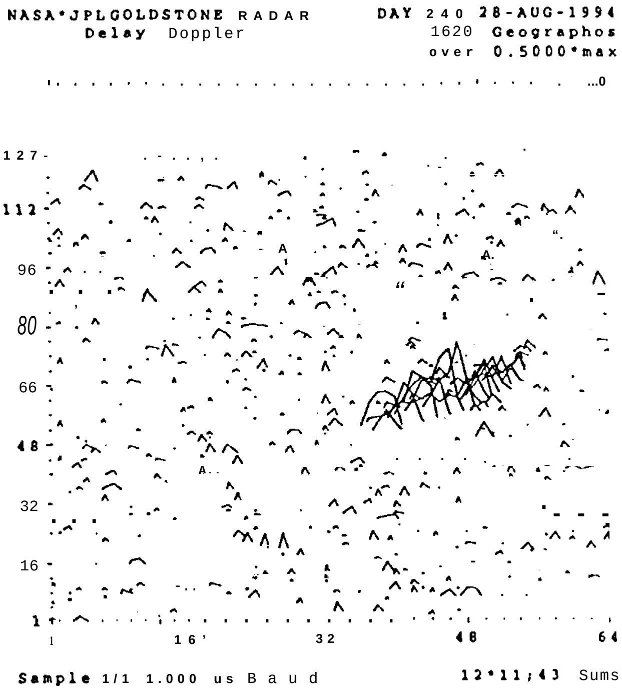

Figure 1 Geographos Radar Image

Range increases toward the top of this figure and frequency (or radial velocity) increases toward the right. The asteroid, rotating clockwise, is illuminated from below. The "leading edge" of the asteroid is seen prominently in this display. The asteroid's orientation is between end-on and broadside, and the spatial extent of the echo is ~4.7 km. The total integration time is 46 s. The data were obtained less than one hour after the beginning of observations on 1994 Aug. 28, the first day of a one-week experiment. Analysis of radar movies from Aug. 28-29 indicates that at the beginning of the Aug. 28 imaging the correction to the range-prediction ephemeris was -10.9 $\pm$ 0.3 km and was becoming more positive at a rate of about 0.16 km/h. (Here "range" is the distance from the asteroid's center of mass to a reference point on the Gold stone 70-m antenna.)

With adequate radar support, it would be possible for a spacecraft lacking onboard optical navigation to be guided into orbit around, or collision course with, an asteroid, For example, consider how Goldstone observations would have shrunk the positional error ellipsoid of Geographos just prior to a Clementine flyby of that target on Aug. 31, 1994. Before the Goldstone observations, the error ellipsoid's typical overall dimension was -11 km. Ranging on Aug. 28-29 and a preliminary shape reconstruction collapsed the ellipsoid's size along the line of sight to several hundred meters, so its projection toward Clementine on its inbound leg would have been 11 x 2 km. Goldstone-VLA radar aperture synthesis could have shrunk the error ellipsoid's longest dimension to about 1 km, about half of Geographos' shortest overall dimension.

The value of a radar observation increases in proportion to the echo strength. A signal-to-noise ratio (SNR) as large as 20 is adequate for detection and useful resolution of the echoes. SNRS greater than 100 let one achieve enough resolution to constrain gross shape characteristics. With SNRS approaching 1000, the data permit detailed constraints on dimensions, and with SNRS at least as large as ~ **3000** one can make images that clearly show surface features. Crudely, one can expect the number of useful pixels in an imaging dataset to be of the same order as the SNR. The spatial equivalent of the uncertainty in delay-Doppler astrometry tied to a target's center of mass is roughly the target's maximum dimension times 10/SNR.

With adequate SNR, spatial resolution, and orientational coverage, delay-Doppler images can be inverted to estimate the asteroid's 3-D shape. Such a reconstruction incorporates parameters for the rotation (the inertia ellipsoid, its orientation with respect to the object's shape, and the object's inertial orientation and spin vector at some initial epoch) and for the delay-Doppler trajectory of the asteroid's center of mass, as well as for the target's radar scattering properties. Under ideal circumstances, topographic features should be identifiable at the several. decameter level and hypotheses about the uniformity of the internal density distribution should be testable.

Delay-Doppler imaging cuts the target into range cells bounded by planes normal to the line of sight, and into radial-velocity cells bounded by planes parallel to both the line of sight and the target's apparent spin vector. A delay-Doppler image can map two or more noncontiguous surface regions onto a single pixel. The images thus constitute a non-intuitive, potentially ambiguous projection whose geometric relation to the surface depends on the target's sky motion as well as its intrinsic rotation. Furthermore, fine frequency resolution requires long coherent integrations and reduction of echo self-noise requires long incoherent summations, but long integrations can introduce image smear from either drift through the prediction ephemeris or rotation. For all these reasons, the 3-D reconstruction constitutes a post-real-time step in NEA radar reconnaissance that is as indispensable as accurate prediction ephemerides are to doing the observations. Moreover, there is a very tight coupling between determinations of a target's 3-D shape, rotation state, and orbit: The most precise predictions of the circumstances of close Earth approaches will be for NEAs whose shapes and spins are best determined.

Echoes from 34 NEAs obtained at the Arecibo and Goldstone facilities have furnished new information about these objects' physical and dynamical properties. Reflectivity and polarization signatures reveal striking diversity in NEA near-surface bulk density and roughness. **1986** DA is significantly more reflective than any other radar-detected asteroid; it may be a 2-km, highly nonconvex (bifurcated?) piece of NiFe metal derived from the interior of a much larger object that melted, differentiated, cooled, and subsequently was disrupted in a catastrophic collision. At the other extreme, the radar signature of 1986 JK suggests a surface bulk density within a factor of two of 0.9 g/cm^3. Similarly, NEA circular polarization ratios, a measure of cm-to-m-scale roughness, range from -0.1 (e.g., 1685 Toro and 1989 JA) to 1.0 (2101 Adonis).

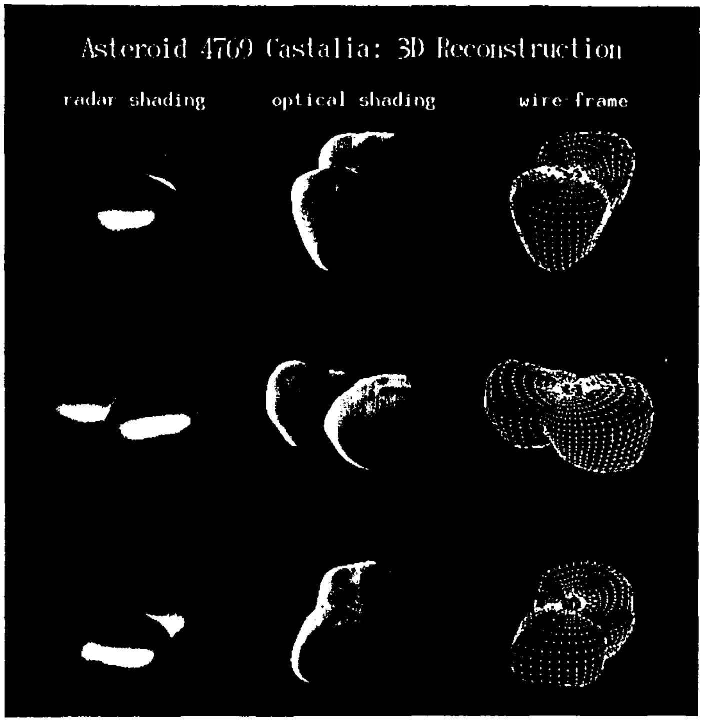

Figure 2 Computer Model Of Asteroid 4769 Castalia

A sequence of Arecibo delay-Doppler images of 4769 Castalia (1989 PB), obtained within two weeks of the asteroid's 1989 discovery, reveal it to consist of two kilometer-sized lobes in contact. Least-squares estimation of Castalia's three-dimensional shape[5] (Figure 2) supports the hypothesis that Castalia is a contact-binary asteroid formed from a gentle collision of two similar-sized fragments, and also constrains the object's near-surface morphology and bulk density. The original delay-Doppler resolution provided pixels 0.3 x 0.17 km; the mean uncertainty in the reconstruction is -0.1 km. In the figure, the left column uses the estimated radar scattering law, the right column shows a wire-grid representation with surface contours at 3° intervals, and the center column uses a Hapke photometric function typical of S-type asteroids; the Earth-asteroid-Sun angle is 37° and the sub-Sun latitude is 35°. In each column the renderings are 90° apart. Comparison of optical lightcurves obtained for Castalia with model lightcurves synthesized using the radar shape model has underscored the asteroid's bifurcation and also has established the pole directing. The radar shape model has been used to model Castalia's gravity field and to explore the orbital dynamics very close to the asteroid[7], with direct application to future spacecraft operations around irregularly shaped NEAs as well as to studies of trajectories of ejects from crater-forming impacts,

Radar observations of 4179 Toutatis during 1992 Dec. 2-19 yielded images placing hundreds to thousands of pixels on the asteroid[6], with fractional astrometric precision as fine as 2 x 10-9 Toutatis has an unusually slow, complex rotation and is bifurcated, although much less so than Castalia. Echoes from several other NEAs show some evidence for bifurcation. Most recently, the radar movies of Geographos reveal a highly elongated pole-on silhouette with two structurally disparate sides.

NEA radar opportunities will expand significantly upon completion of upgrades in the Arecibo telescope, which by 1996 should be producing thousand-pixel images of several NEAs annually. A dedicated optical search program (the Spaceguard Survey) could discover some 100,000 NEAs, most of which could, in principle, be studied with groundbased radar at least once every few decades. However, Arecibo and Goldstone are already heavily oversubscribed, so observation of more than a small fraction of the objects discoverable in proposed optical surveys will require dedicated radar telescopes.

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